Chemical Evolution models of Local Group galaxies

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Status quo and perspectives of standard chemical evolution models of Local Group galaxies are summarized, discussing what we have learnt from them, what we know we have not learnt yet, and what I think we will learn in the near future. It is described how Galactic chemical evolution models have helped showing that: i) stringent constraints on primordial nucleosynthesis can be derived from the observed Galactic abundances of the light elements, ii) the Milky Way has been accreting external gas from early epochs to the present time, iii) the vast majority of Galactic halo stars have formed quite rapidly at early epochs. Chemical evolution models for the closest dwarf galaxies, although still uncertain so far, are expected to become extremely reliable in the nearest future, thanks to the quality of new generation photometric and spectroscopic data which are currently being acquired.

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1. Introduction

The proximity of Local Group galaxies makes them the ideal benchmarks to study galaxy formation and evolution, because they are the only systems where the accuracy and the wealth of observational data allows us to understand them in a sufficiently reliable way. In fact to understand the evolution of galaxies, astronomers must follow two distinct and complementary approaches: on the one hand they must develop theoretical models of galaxy formation, of chemical and dynamical evolution, and, on the other hand, they must collect accurate observational data to constrain the models. Of particular importance is to acquire reliable data on the chemical abundances, masses and kinematics of the galactic components (gas, stars, dark matter), on the star formation (SF) regimes, and on the stellar initial mass function (IMF), quantities that are much better derivable in nearby systems.

Following Socrates' indication, $\gamma\nu\hat{\omega}\theta\iota\ \sigma\alpha\upsilon\tau\acute{o}\nu$ (*know thyself*), that the knowledge of truth must be derived not from metaphysics but from critical analysis of the reality, here I try to critically review *status quo* and perspectives of standard chemical evolution models, warning that this kind of models, although quite successful, refer only to large-scale, long-term phenomena, and cannot account for the small-scale, short-term variations often observed in the chemical and dynamical properties of galaxies.

2. Parameters

The major parameters involved in standard chemical evolution models are:
- SF law and rate (often simplisticly approximated either as exponentially decreasing functions of time, SFR $\propto e^{-t/\tau}$, or as power laws of the gas density, e.g. SFR $\propto \Sigma^n_{gas}$);
- Gas flows in and out of the considered region (the infalling gas rate being usually approximated with an exponentially decreasing function of time, $f_i \propto e^{-t/\theta}$, and the galactic outflows, or winds, assumed to be proportional to the energy released by Supernova explosions, $f_w \propto E_{SN}$);
- IMF (usually represented as a power law, $\phi \propto m^{-\alpha}$ with one or more exponents α for different mass ranges, see Gallagher & Grebel, this volume);
- Stellar lifetimes and nucleosynthesis yields.

Some of them, however, are implicitely linked to other parameters, such as, for instance, the amount of mixing occurring in stellar interiors or the stellar mass loss rates.

Since the parameters are many, the crucial prescription to avoid misleading results from chemical evolution modeling is to **always compare the model predictions with all the available constraints**, not only with those relative to the examined quantities. This prescription implies that, until now, Galactic models are much better constrained than those for external, less studied systems. In the following they are then discussed separately.

3. The Galaxy

In the case of the Galaxy, the observational constraints formally outnumber the model parameters. Indeed, in the last two decades, an increasing number of accurate and reliable data have been accumulated that allow us to put stringent limits on the evolution of the Milky Way. The *minimal* list of data that should always be compared with the model predictions (see also Boissier & Prantzos 1999) includes:

• current distribution with Galactocentric distance of the SFR (e.g. as compiled by Lacey & Fall, 1985);
• current distribution with Galactocentric distance of the gas and star densities (see e.g. Tosi, 1996, Boissier & Prantzos 1999 and references therein);
• current distribution with Galactocentric distance of element abundances as derived from HII regions and from B-stars (e.g. Shaver et al. 1983, Smartt & Rollerston 1997);
• distribution with Galactocentric distance of element abundances at slightly older epochs, as derived from PNe II (e.g. Pasquali & Perinotto 1993, Maciel & Chiappini 1994, Maciel & Köppen 1994, Maciel et al. 2003);
• age-metallicity relation (AMR) not only in the solar neighbourhood but also at other distances from the center (e.g. Edvardsson et al. 1993);
• metallicity distribution of G-dwarfs in the solar neighbourhood (e.g. Rocha-Pinto & Maciel 1996);
• local Present-Day-Mass-Function (PDMF, e.g. Scalo 1986, Kroupa et al. 1993);
• relative abundance ratios (e.g. [O/Fe] vs [Fe/H]) in disk and halo stars (e.g. Barbuy 1988, Edvardsson et al. 1993).

There are now several models able to reproduce all these observed properties. Even if this circumstance does not provide yet a unique detailed scenario for the formation and evolution of the Milky Way, it allows us to make robust predictions on several important issues.

An example of robust prediction resulting from the requirement of reproducing all the above list of data is the Galactic evolution of deuterium, one of the elements produced during the Big Bang and one of the best baryometers (see Steigman, this volume). When people began to study the evolution of D (e.g. Steigman & Tosi 1992, Galli et al. 1995, Prantzos 1996), observational data on the D abundance were available only for the local interstellar medium (ISM) and for the Protosolar Cloud (Linsky 1998, Geiss & Gloeckler 1998 and references therein). All the models able to reproduce the above list of constraints (see Tosi 1996 and references therein) predicted only a moderate depletion of D from its primordial value to the present one: a factor of 3 at most (see Fig.1). This implies a primordial number ratio to hydrogen $(D/H)_p \leq (4-5)\times10^{-5}$ impossible to reconcile, within the framework of standard Big Bang nucleosynthesis (SBBN), with the low primordial abundance by mass of ^{4}He, $Y_p \simeq 0.23$ inferred earlier on by several groups from low metallicity HII regions and globular clusters. These Y_p determinations have subsequently become the subjects of hot debates (see Steigman, this volume, and

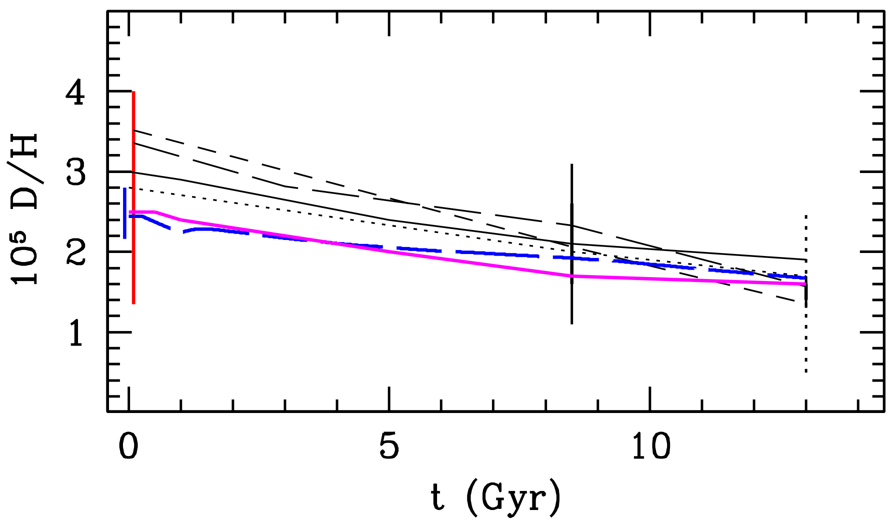

FIGURE 1. Deuterium evolution in the solar ring as predicted by various models: solid line, Steigman & Tosi 1992; short-dashed line, Galli et al. (1995); dotted line, Prantzos (1996); long-dashed line, Chiappini et al. (1997). The thick solid line and the thick long-dashed line are both from Romano et al. 2003. All the vertical lines correspond to data derived from observations; from left to right they are: the primordial D/H derived from WMAP, the range of abundances inferred from high-redshift QSO absorbers, the pre-solar value, and the local ISM value (see text for references). The dotted line at 13 Gyr shows the range of D/H ratios derived along different lines of sight (e.g. Vidal-Madjar et al. 1998, Sonneborn et al. 2000).

references therein, for a critical discussion of this result), but, at the time, this inconsistency led some people think that the Galactic models were wrong and that we should find a way to deplete much more D during the Galaxy evolution, to allow for a higher primordial abundance. Then high-redshift, low-metallicity QSO absorbers started to be observed and provided D/H always lower than 4×10^{-5} (e.g. Burles & Tytler 1998 and references therein), perfectly consistent with the predictions of the Galactic models with low D depletion (see Fig.1, Tosi et al. 1998, Chiappini et al. 2003). However, concerns remained that, despite their low-metallicity, high-redshift absorbers might have D contents lower than primordial, because some stellar activity could have already taken place there and burnt some of the original D. Eventually, a few months ago, the microwave satellite WMAP has provided a direct estimate of the baryon-to-photon ratio, which corresponds, within the SBBN framework, to a primordial $(\mathrm{D/H})_p = (2.62 \pm 0.30) \times 10^{-5}$ (Spergel et al. 2003). This value is again in excellent agreement with the predictions of Galactic chemical evolution models aimed at reproducing the complete set of observational contraints (cfr. thick lines in Fig.1, Romano et al. 2003) and shows how robust model predictions could be when sufficiently constrained. On the other hand, the significant variations of the D abundances measured in the local ISM along different lines of sight (dotted vertical line in Fig.1) indicate that more sophisticated models would be needed to reproduce also local fluctuations (see also Pilyugin & Edmunds 1996).

What have we learnt on the Galaxy formation and evolution from chemical evolution models ? One of the main results, in my opinion, is that the Milky Way has not formed from a very rapid monolithic collapse of a single proto-galaxy. We have recent observational evidences that the Galaxy is accreting the Sagittarius dwarf (e.g. Ibata et al. 1995), it is likely that it will accrete the Magellanic Clouds in the future and someones (e.g. Dinescu et al. 1999, Hilker & Richtler 2000, Ferraro et al. 2002) think that ωCentauri is

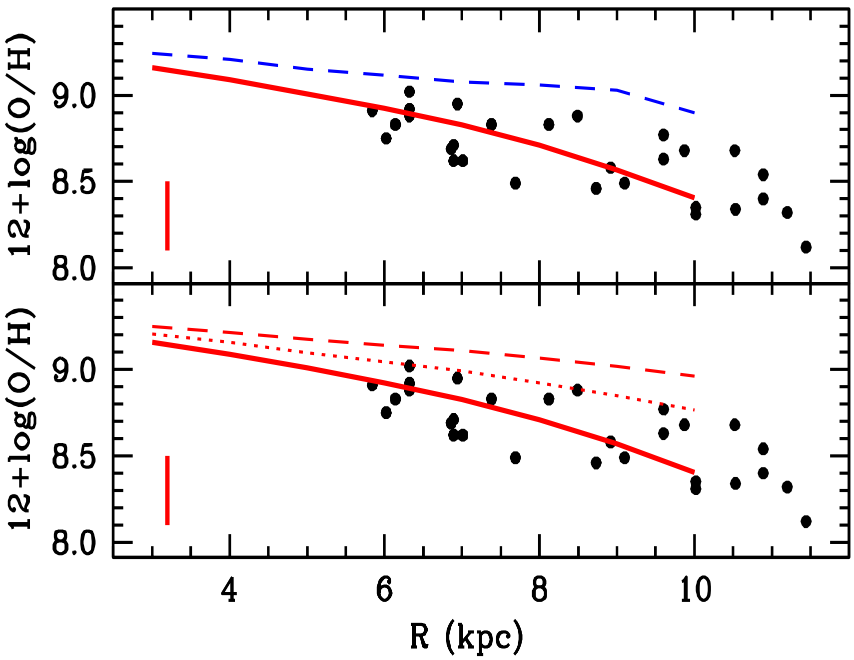

FIGURE 2. Radial distribution of the Galactic oxygen abundance at the present epoch, as derived from HII regions observations (dots) and as predicted by chemical evolution models (Tosi 1988 a, b). Top panel: models with primordial infall (solid line) and without any infall after disk formation (dashed line). Bottom panel: models with infall of different metallicity (solid line for Z_i=0, dotted for Z_i=1/2 $Z_\odot$, short-dashed for Z_i=$Z_\odot$). See text for details.

also an accreted small dwarf, rather than a real globular cluster. In addition, chemical evolution models already showed earlier on (e.g. Tinsley 1980, Tosi 1988 a, b, Matteucci & François 1989, Chiappini et al. 1997, Boissier & Prantzos 1999) that the Milky Way must have kept accreting metal poor gas at a relatively steady rate.

Historically, one of the first reasons to invoke a continuous infall of metal poor gas on the Galactic disk was the so-called G-dwarf problem (see Wyse, this volume), i.e. the fact that, without infall, chemical evolution models overpredict the number of low-metallicity long-lived stars. There are however other observed properties that need infall to be reproduced. Figs 2 and 3 show two examples of this need. In Fig.2 the radial distribution of the current oxygen abundance in the disk is plotted as a function of Galactocentric distance. In both panels the dots corresponds to HII regions values and the curves to the predictions of Tosi (1988 a and b) models. When a constant equidense infall of primordial gas is assumed (solid line in the top panel), the models reproduce very well the observed distribution, whilst without any infall after the disk formation (dashed line in the top panel) they predict an abundance gradient flatter than observed and overproduce oxygen at the present epoch at all galactocentric distances. The bottom panel of Fig.2 illustrates why the accreted gas should be metal poor: the solid line, as in the top panel, corresponds to a metal free infall and is in excellent agreement with the data; the dashed line corresponds to the same model, but assuming a solar infall metallicity, and clearly overpredicts oxygen; the dotted line assumes a half-solar metallicity and also overpredicts oxygen.

Fig.3 shows the age-metallicity relation in the solar neighbourhood, as derived by

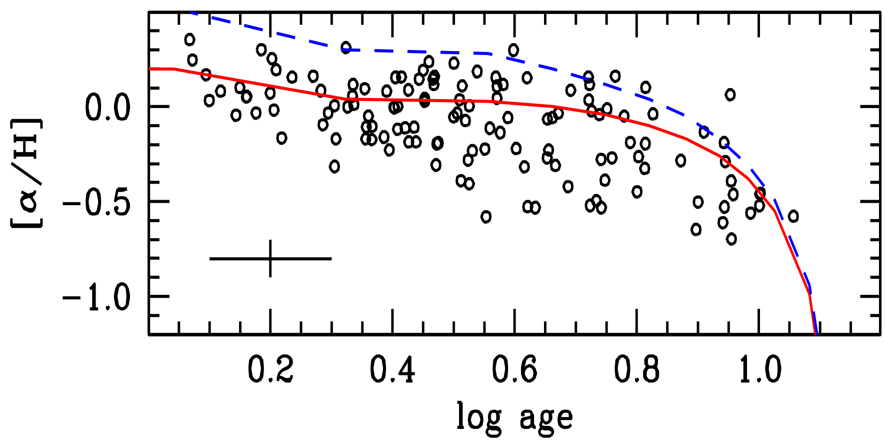

FIGURE 3. Age-metallicity relation in the solar neighbourhood as derived from field star observations (dots) and as predicted by the models (lines) of the top panel of Fig.2. See text for details.

Edvardsson et al. (1993) from observations of F and G dwarfs and as predicted by the same models of the top panel of Fig.2. Again, the model assuming a constant infall of primordial gas (solid line) fits well the data, while the model with no infall after the disk formation (dashed line) overproduces the metallicity since quite early epochs. To reproduce both the observed radial gradients and abundances, nowadays all chemical evolution models assume a fairly conspicuous amount of steady gas accretion (but see also Lacey & Fall 1985). Most authors assume this gas to be primordial, but it was shown (Tosi 1988b) that it could reach a metallicity up to 0.2 $Z_\odot$ without loosing its diluting effects on the predicted abundances. This metallicity happens to be that derived for the few high-velocity clouds falling on the Galactic disk, where abundance measurements are possible (e.g. DeBoer & Savage 1983).

Another important result is that both observations and chemical evolution models suggest that the halo of the Galaxy must have created fairly rapidly most of its present stars. One of the main reasons to reach this conclusion comes from the abundance ratios between alpha elements (those produced directly from ^{4}He burning, like oxygen and magnesium) and iron. Iron is mostly produced by Supernovae of type Ia (intermediate mass stars in binary systems) while alpha elements are synthesized essentially in massive stars. The different lifetimes of their main producers imply that the enrichment of the alpha elements is very rapid (within a few Myr) while that of iron starts to occur after $\sim$100 Myr and has its bulk about 1 Gyr after the onset of the SF activity. As shown by Matteucci (1992) this circumstance makes the stellar [α/Fe] measured in a region an excellent indicator of its SF regime. The curves in Fig.4 display the different behaviours predicted by Matteucci's models for different SF regimes. In regions, where the SF is supposed to be continuous over several Gyrs, stars can form when iron has had plenty of time to enrich the medium and contribute to their initial metallicity. Hence, the stellar [α/Fe] is predicted to steadily decrease when iron increases (solid line in Fig.4). Vice versa, in regions, like bulges, where the SF is very rapid and intense, all the stars form prior to the release of iron by SNe Ia, and contain many α but little iron, thus showing a plateau (dashed line) with high [α/Fe]. In the solar neighbourhood, where some stars belong to the halo and others to the disk, Matteucci's models predict (dotted line) a fairly flat and high [α/Fe] vs [Fe/H] for the halo stars with low [Fe/H] and a decreasing [α/Fe]

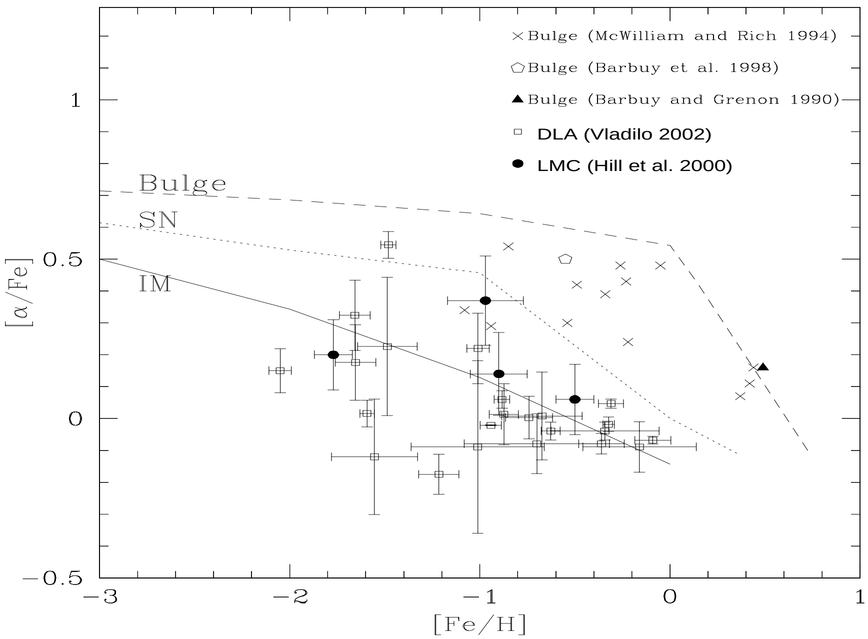

FIGURE 4. The lines show Matteucci's model predictions for the α/Fe ratios for different SF regimes. See Matteucci (2003) for references and details.

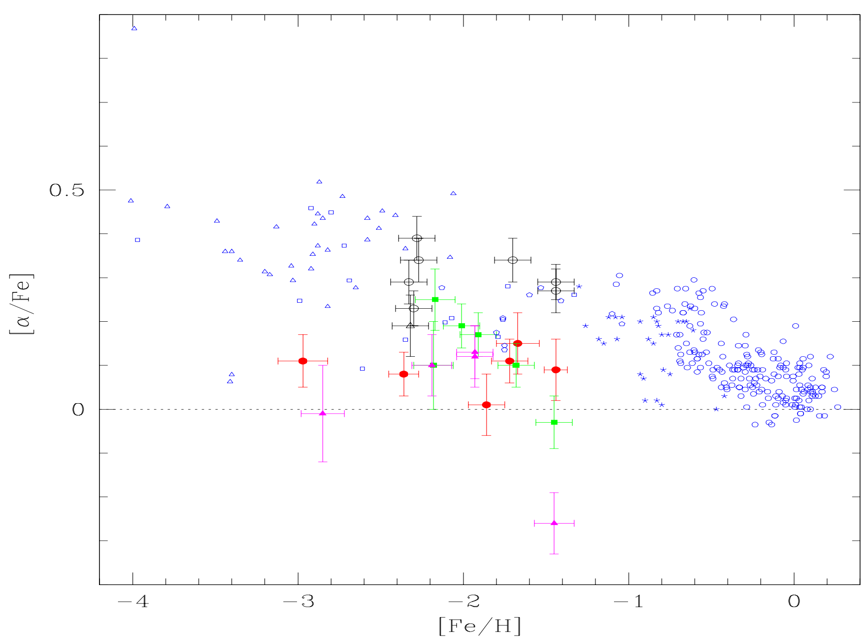

FIGURE 5. α/Fe observed in different environments. Open circles refer to local disk stars, open triangles to local halo stars, open symbols with error bars to Galactic globular clusters and filled symbols with error bars to dSphs (Shetrone et al. 2001, and references therein).

vs [Fe/H] for disk stars with higher [Fe/H]. Since this is indeed the observed behaviour (see Fig.5), this indicates that the halo must have had a strong and rapid initial SF activity and the disk a continuous one.

Fig.5 shows [α/Fe] vs [Fe/H] as derived from spectroscopy of stars in various environments (Shetrone et al. 2001, and references therein). The small open circles correspond to solar neighbourhood disk stars, the triangles to halo field stars, the larger open circles with error bars to halo clusters, and they show an overall distribution quite similar to that predicted by Matteucci's models. The filled symbols refer instead to stars observed in nearby dwarf spheroidals (dSphs) and they all show [α/Fe] systematically lower than those measured at the same [Fe/H] in Galactic stars. Further high-resolution spectroscopy of stars in other nearby dSphs (Tolstoy et al 2003), including Sagittarius (Vladilo et al. this conference and Bonifacio et al. 2003), have confirmed this systematic difference. This evidence makes it extremely unlikely that our halo have formed mostly from the merging of dwarf galaxies like these, because there is no conceivable mechanism able to make iron-poor, alpha-rich stars assembling alpha-poor, iron-rich ones. From this and other arguments (see Tosi 2003, and Wyse, this volume) it seems more likely that our Galaxy has mainly formed from mostly gaseous building blocks and within a relatively short timescale (a couple of Gyr, at most).

Despite the numeorus important achievements of chemical evolution modeling, there are important aspects of the Galaxy formation and evolution not well understood yet. Has the thin disk formed before or after the thick disk ? Where is the infalling gas coming from ? Is it actually as metal poor and as steady as required ?

A clear example of our lack of detailed knowledge of the processes leading to the oberved Galactic properties is the evolution of the abundance gradients in the disk. There are several chemical evolution models able to reproduce the present metallicity gradients derived from HII regions and young stars (e.g. Fig.2), along with the whole set of constraints listed above. These models, however, differ from each other in several assumptions and one of the major effects of such differences is that they predict quite different evolutions of the gradient (see e.g. Tosi 1996 and references therein): some predict the gradient to steepen with time while others predict it to flatten. It is still difficult to understand what the actual evolution is, because the available data refer mostly to relatively young objects. Older single stars are in fact fainter and hence more difficult to measure, specially at the large distances required to derive the gradient with sufficient radial baseline. PNe in principle are a good tool for this purpose, but the interpretation of their data in terms of progenitor age is still rather uncertain and the progenitors of the safest ones are stars a few Gyr old. The best targets to get a reliable gradient back to the earliest epochs are open clusters, since they are much less affected than individual objects by uncertainties on age, distance and metallicity. Several people have derived the abundance gradient from open cluster data (see e.g. Friel 1995 and references therein), but what is needed for a robust result on the gradient evolution is a cluster sample large enough to provide significant results in each age bin, and with ages, metallicities and distances derived in a homogeneous way to avoid spurious effects (e.g. Bragaglia et al. 2002). Building up such a sample clearly takes time, but we are confident that the results will be rewarding.

4. Other Local Group galaxies

The chemical evolution of M31 and M33 (as well as that of other spirals outside the Group) has been modeled by a few groups with approaches similar to those applied to the Milky Way (e.g. Diaz & Tosi 1984, Mollà et al. 1996). These models predict that the

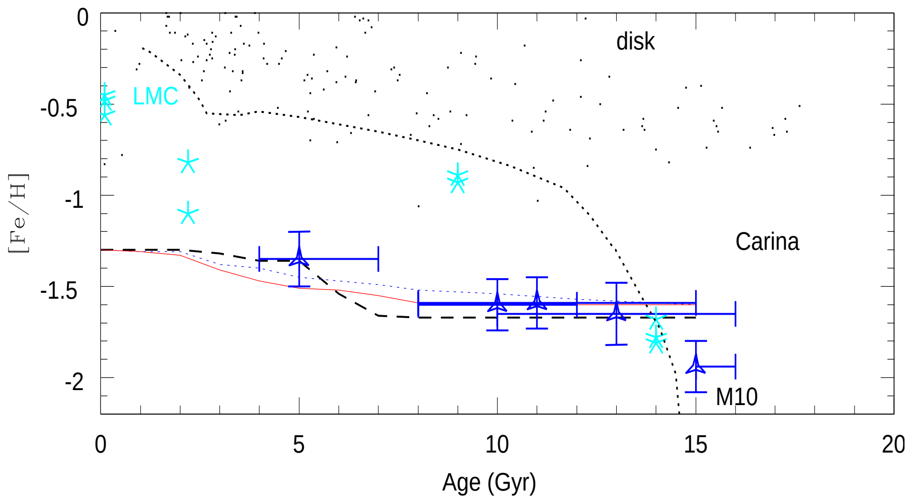

Figure 6. AMR derived from VLT/UVES spectroscopy of the dSph Carina (triangles with error bars) by Tolstoy et al. (2003). Also shown for comparison are the data relative to LMC clusters (asterisks), Pagel & Tautvaisiene AMR from LMC clusters (dotted line) and the data by Edvardsson et al. (1993) for solar neighbourhood stars (dots).

disks of these systems have a roughly continuous SF, with shorter timescales for earlier type spirals and longer ones for later type spirals. Infall of metal poor gas is required also for M31 (and other massive spirals) whilst it is not necessary in low mass spirals like M33. These models, however, are not as well constrained as those for the Galaxy, since, at least until recently, the only data useful for chemical evolution modeling were the HII region abundances and the gas and star density distributions in the disks.

The data available for dwarf galaxies were equally scarse, but this kind of systems have intrigued many more scientists. In the last 25 years there has been a wealth of papers dealing with the chemical evolution of dwarfs (starting e.g. with Lequeux et al. 1979 and Matteucci & Chiosi 1983): a rather frustrating challenge, if one considers how inconsistent with each other the results of these papers have been. While most authors agreed that the IMF in these galaxies is fairly similar to Salpeter's, both on the SF regimes and on the existence of galactic winds different groups have reached very different conclusions. For instance, many groups suggested that the SF in all dwarfs is episodic (e.g. Matteucci & Chiosi 1983, Pilyugin 1993, Larsen et al. 2001), but others argue that in late-type dwarfs the SF is continuous (e.g. Carigi et al. 1995, Legrand 2001). For the gas flows, some authors (e.g. Gilmore & Wyse 1991) concluded that winds triggered by SN explosions are not needed to explain the observed chemical abundances. However, other authors reached the opposite conclusion that the winds are the only viable mechanism to predict abundances as low as observed; some (e.g. Matteucci & Tosi 1985, Pilyugin 1993, Recchi et al. 2002) arguing that the outflowing gas must be enriched in the elements produced by SNe and others (e.g. Pagel & Tautvaisiene 1998, Larsen et al. 2001) arguing, instead, that the outflowing gas has the same composition as the galaxy medium. In other words, all kinds of possible scenarios have been attributed to the evolution of dwarf galaxies.

These inconsistencies are due to the lack of adequate observational data. Many groups, for instance, to model dwarf galaxy evolution have adopted the age-metallicity relation presented by Pagel & Tautvaisiene (1998) for the LMC (dotted line in Fig.6). However, the LMC is not a prototype for any kind of dwarfs, and the AMR was derived from

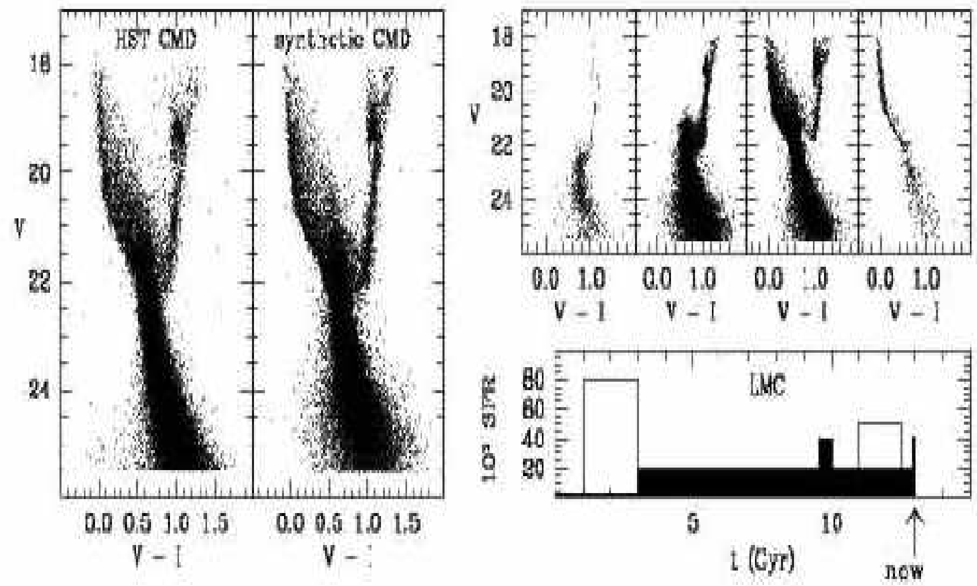

FIGURE 7. From the Coimbra experiment (Skillman & Gallart 2002). Left-hand panel: CMD of a field of the LMC bar derived by Smecker-Hane et al. (2002) from HST/WFPC2 photometry; second panel from left: the corresponding best synthetic CMD by Tosi et al (2002). Top right panels: the synthetic CMD of the previous panel splitted in its four episode components, from the oldest to the youngest one from left to right. Bottom-right panel: the resulting SF history, i.e. SF rate per unit area (in units of 10^3 $M_{\odot}yr^{-1}kpc^{-2}$) vs time is shown as filled histogram. The empty histogram refers to the SF history derived from LMC star clusters.

clusters data, which do not necessarily have the same evolution of field stars (see, in fact, Fig.7). I believe, however, that the quantity and quality of the observational data on nearby dwarfs is so dramatically improving today that our understanding of dwarfs evolution will make an impressive step forward in the near future. Indeed:

1) High resolution spectrographs at 10 m class telescopes are providing in these months a wealth of new accurate abundances for field stars in nearby dwarfs. The ages of these stars can be derived from the colour-magnitude diagrams (CMDs) resulting from deep high resolution photometry, both from ground and space. Fig.6 draws the first results by Tolstoy et al. 2003 from VLT/UVES observations and shows how different is the AMR of LMC clusters and of Milky Way field stars from the AMR of the stars in the Carina dwarf galaxy (as well as in the other dwarfs of their program).

2) Deep and tight CMDs provide reliable information on the IMF of the observed regions (see e.g. Gallagher & Grebel, this volume) and on the SF history of the observed regions.

The SF history is quite reliably derivable by interpreting the observational CMDs with the synthetic CMD method (e.g. Tosi et al. 1991), which has proven a powerful and robust tool, recently tested on an LMC field comparing the scenarios obtained by different groups (the so-called *Coimbra experiment*, see Skillman & Gallart 2002 and references therein). Fig.7 shows in the bottom-right panel the SF history of the field on the bar of the LMC as derived by our group (Tosi et al. 2002) applying the synthetic CMD method to the CMD obtained by Smecker-Hane et al. (2002) from HST/WFPC2 photometry, and kindly provided for the Coimbra experiment. It is apparent that such beautiful data let them measure with sufficient accuracy even the oldest/faintest stars,

thus allowing for the derivation of the SF history back to the earliest epochs. The SF history in this field of the LMC (filled histogram in Fig.7) is fairly continuous, although with significant variations in the rate, and quite different from that inferred by Pagel & Tautvaisiene (1998) from cluster data (empty histogram).

The combination of these high quality photometric and spectroscopic data, with appropriate interpretation tools, will soon allow us to know the AMR, the SF history and the IMF of nearby galaxies. Being the closest galaxies, the Magellanic Clouds are in the best position to allow for accurate and extensive data sets on these quantities. Hence, HST photometry and 10 m class telescope spectroscopy can put us in a few years in the conditions of modeling their chemical evolution even more safely than that of the solar neighourhood. This opens new promising horizons to chemical evolution studies of dwarf galaxies in general and of late-type dwarfs in particular. Taking into account that the SMC can be considered a prototype for this kind of galaxies, because it has their typical mass, gas fraction and metallicity, this would imply an unprecedented step forward to understand the evolution of galaxies that not only are the most numerous ones, but are also those that can provide better clues to galaxy formation processes. This will confirm, once again, that the Local Group is the best astrophysical laboratory to understand galaxy evolution.

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